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Arik et al.

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(54) **METHOD AND APPARATUS FOR IMPROVED COOLING OF A HEAT SINK USING A SYNTHETIC JET**

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Related U.S. Application Data

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(51) **Int. Cl.**
F28F 3/02 (2006.01)
H01L 23/467 (2006.01)

(52) **U.S. Cl.**
CPC ***F28F 3/022*** (2013.01); ***H01L 23/467*** (2013.01); *H01L 2924/0002* (2013.01); *Y10T 29/4935* (2015.01)

(58) **Field of Classification Search**
CPC F28F 3/022; H01L 23/467; F04B 41/06; F04D 25/16; F04D 25/166; F04F 5/54
USPC 165/80.3, 96, 908; 361/695, 697
See application file for complete search history.

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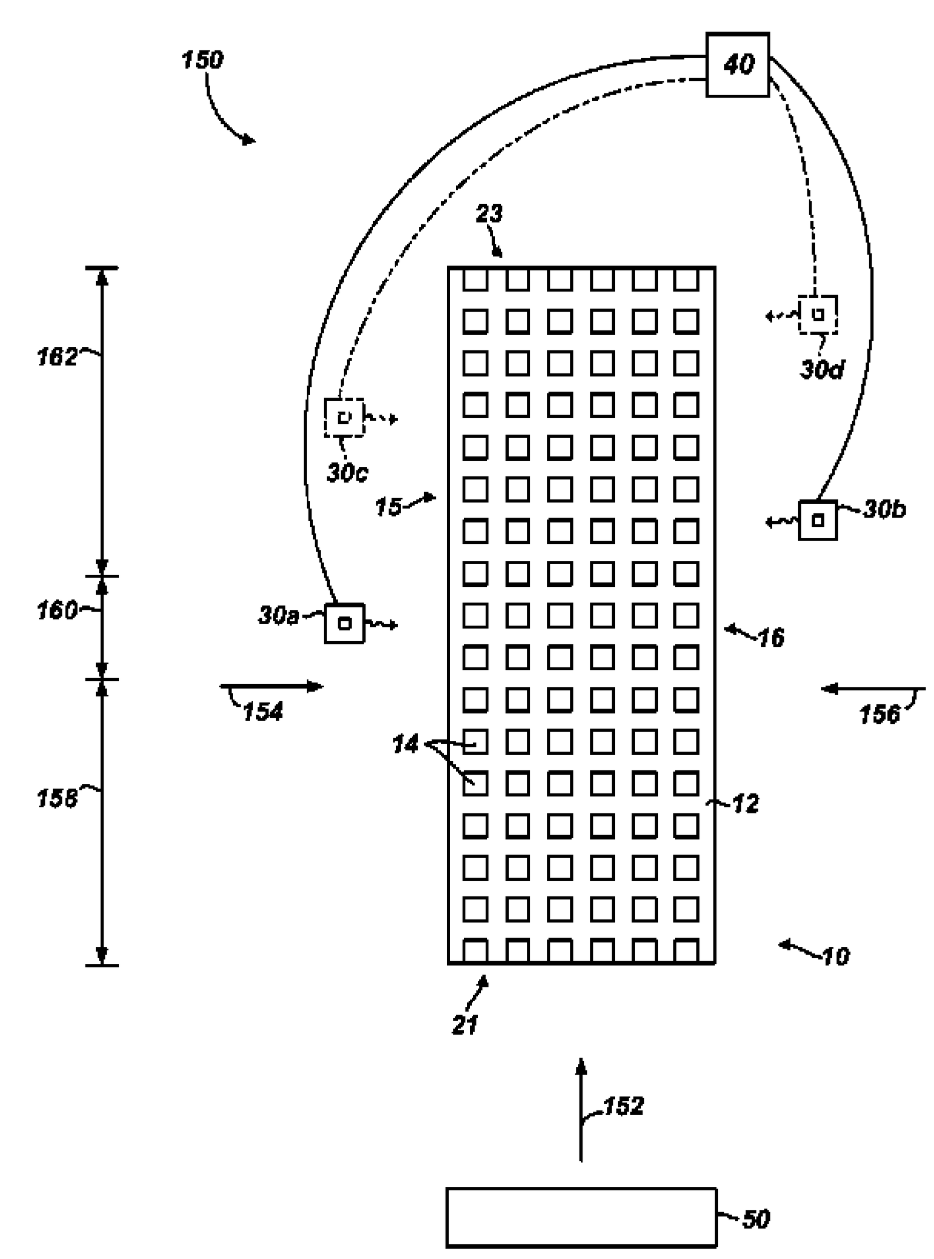
(57) **ABSTRACT**

A system for cooling a device includes a heat sink comprising a substrate having a plurality of fins arranged thereon, a fan positioned to direct an ambient fluid in a first direction across the heat sink, and a first synthetic jet assembly comprising one of a multi-orifice synthetic jet and a plurality of single orifice synthetic jets. The first synthetic jet assembly is configured to direct the ambient fluid in a second direction across the heat sink, wherein the second direction is approximately perpendicular to the first direction.

20 Claims, 9 Drawing Sheets



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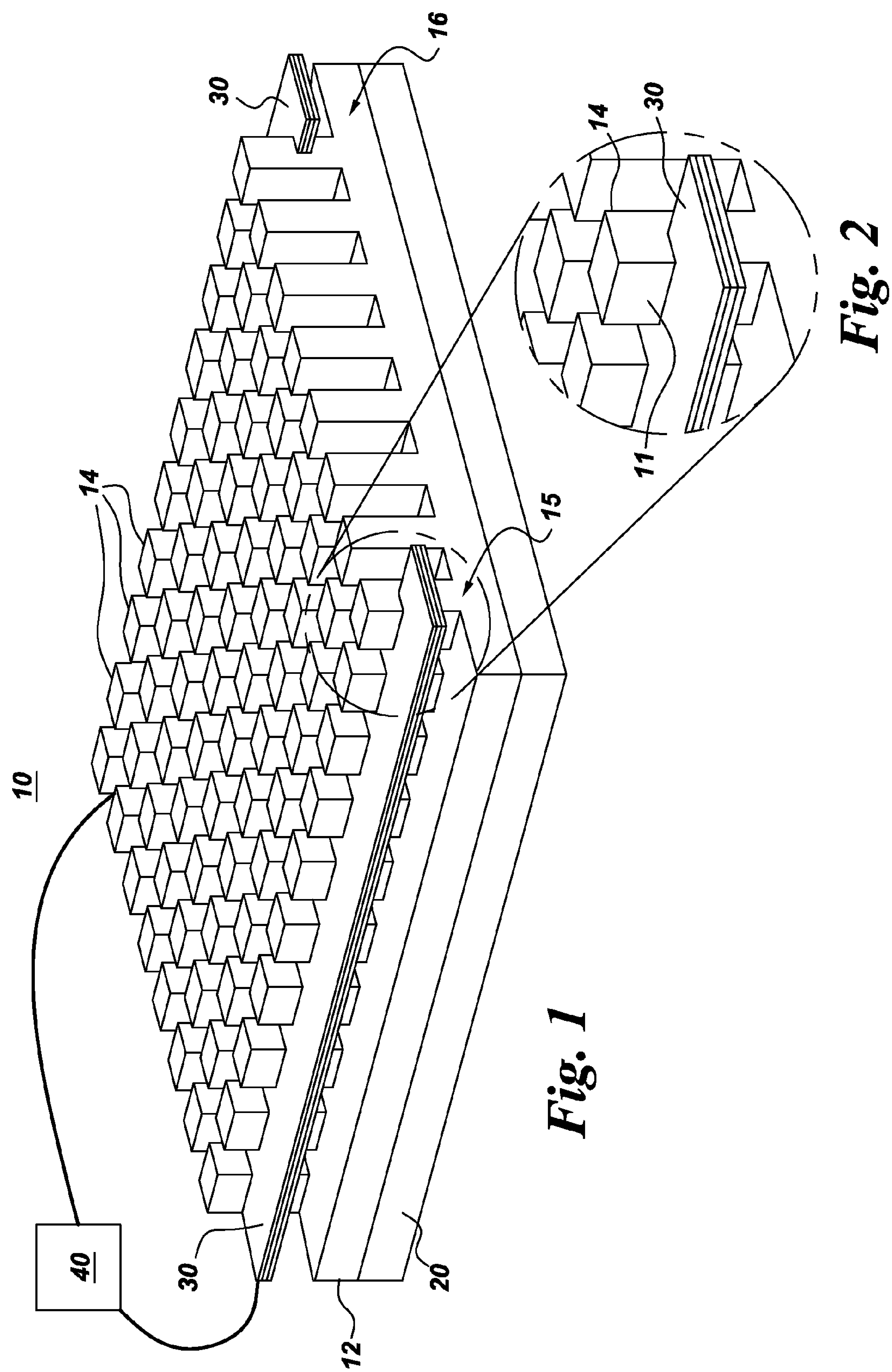

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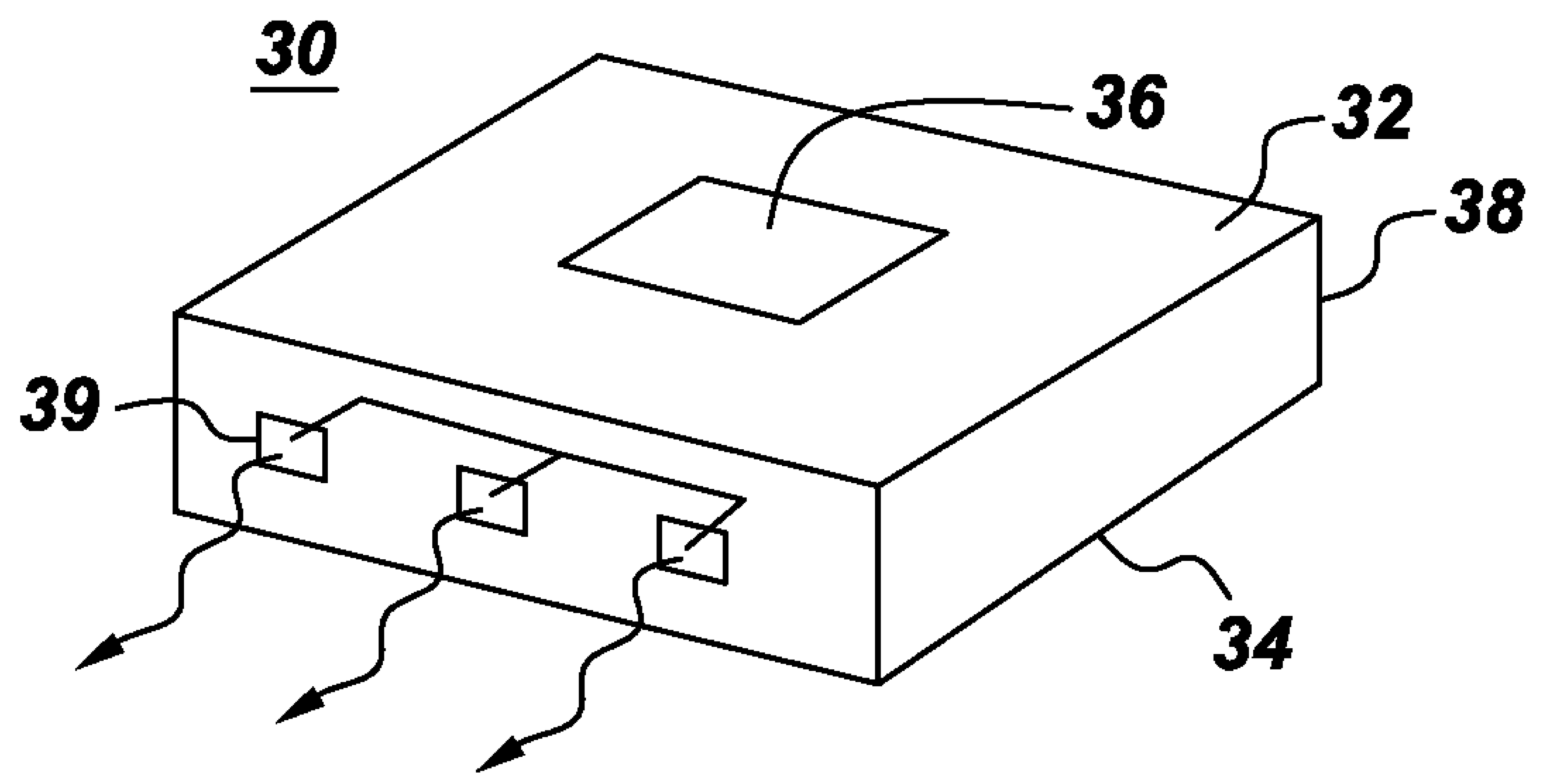
Fig. 2



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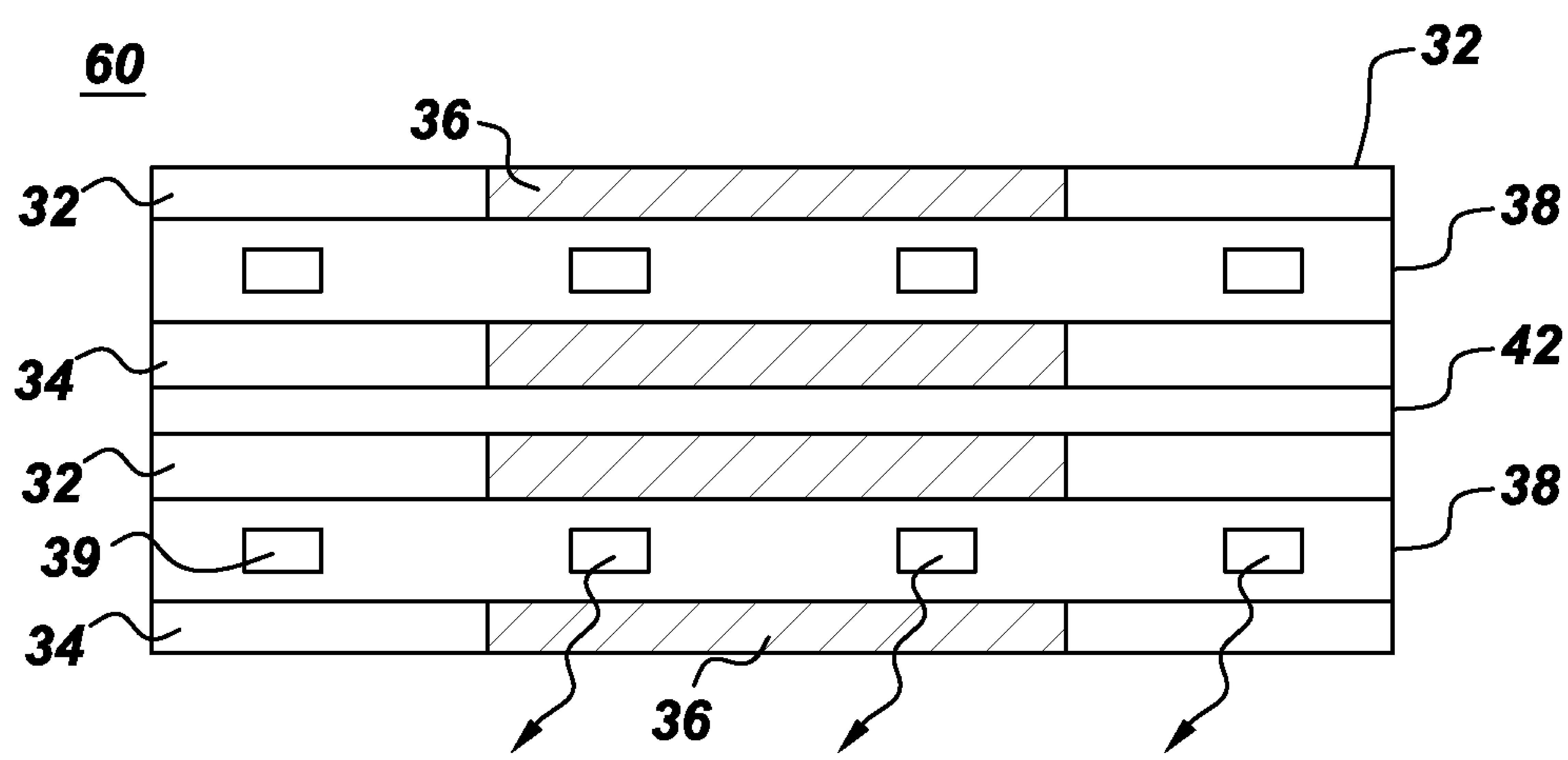

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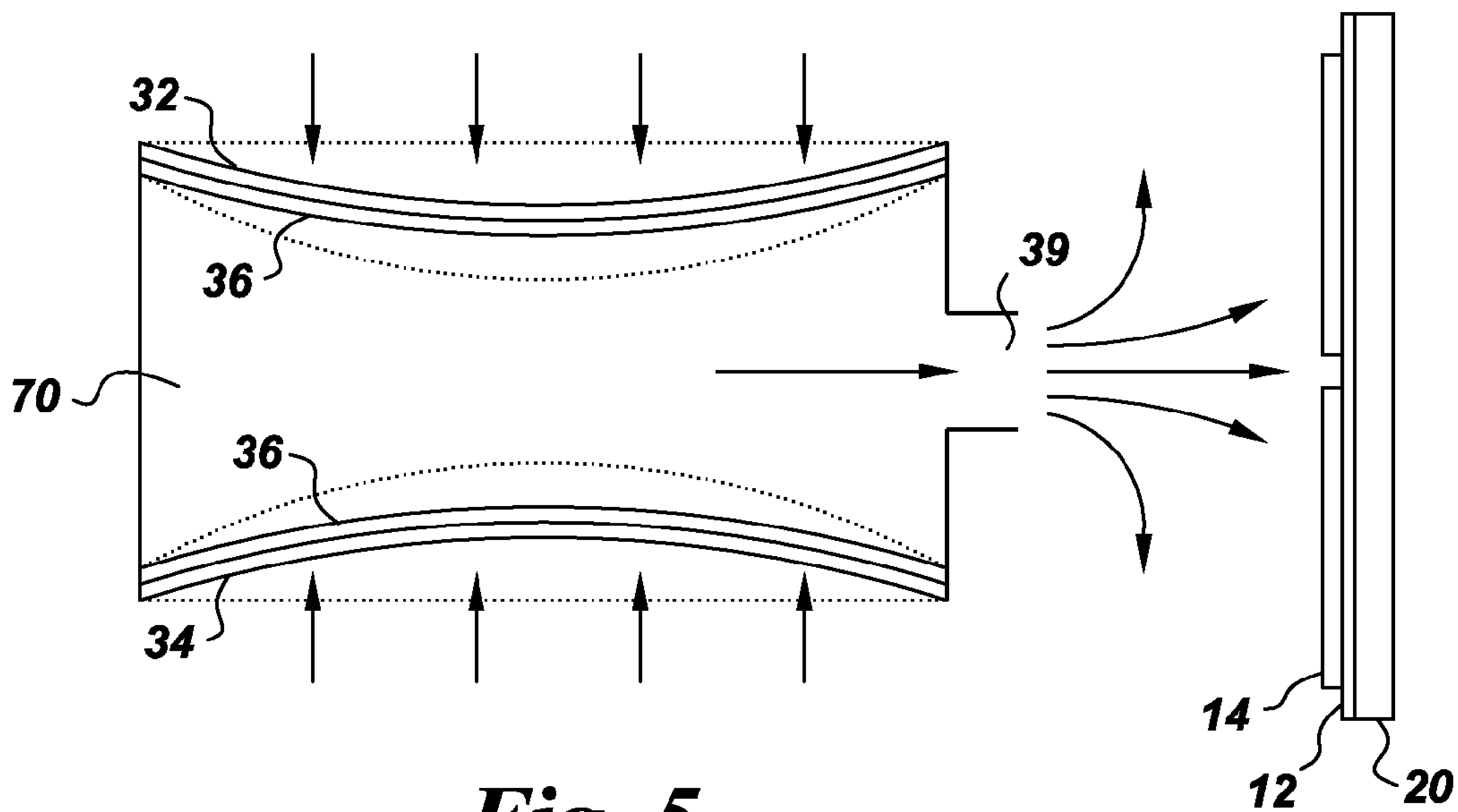

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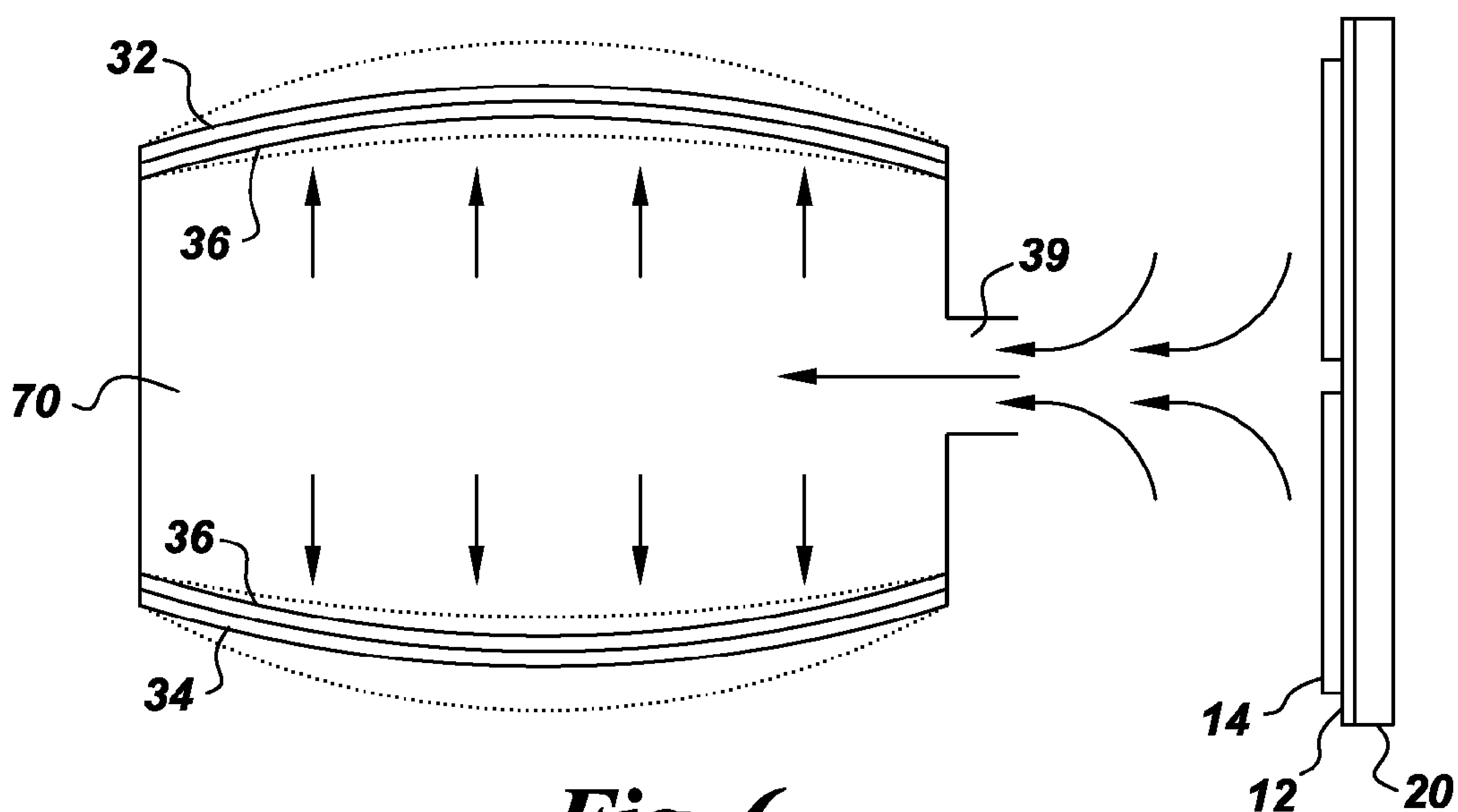

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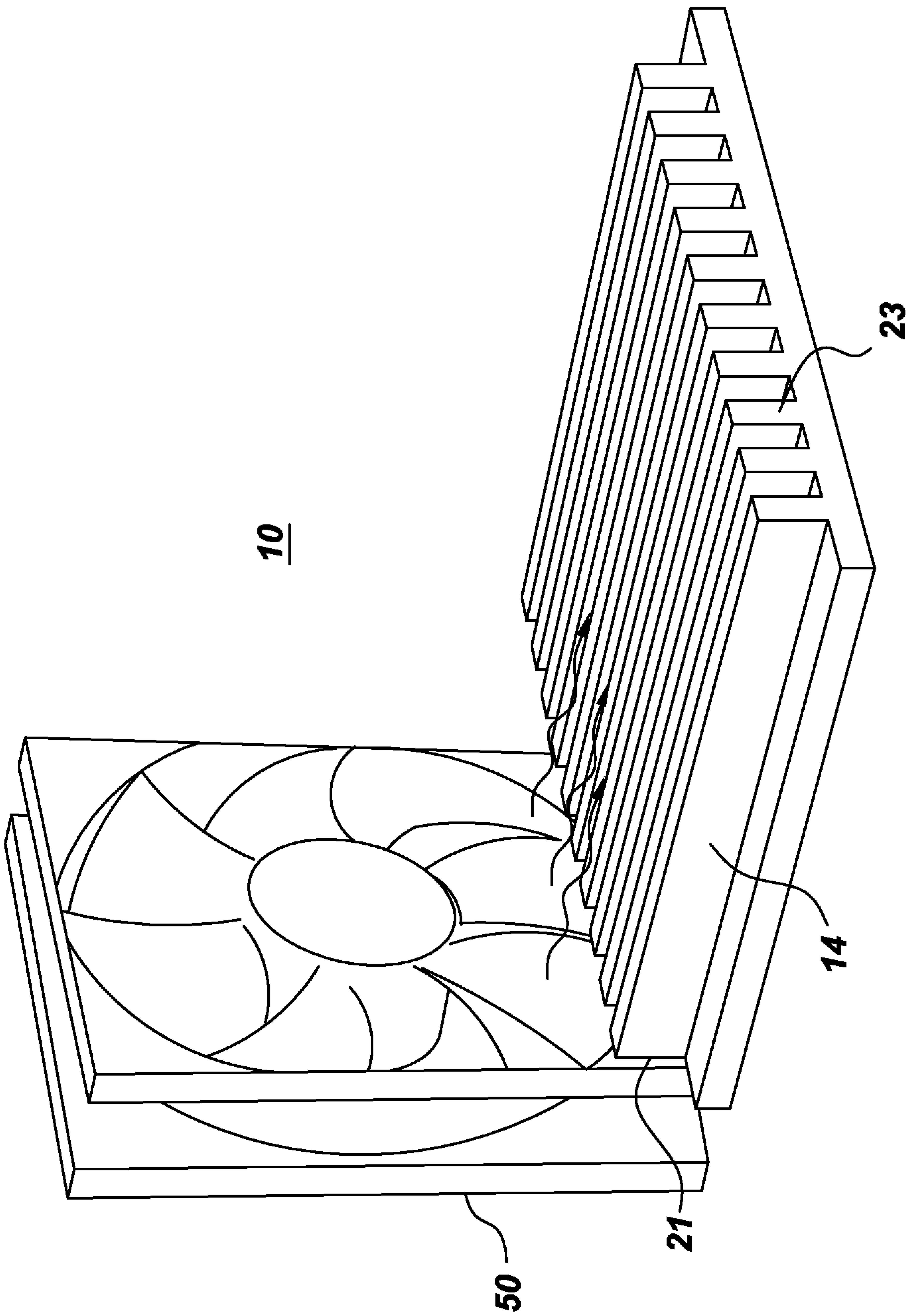

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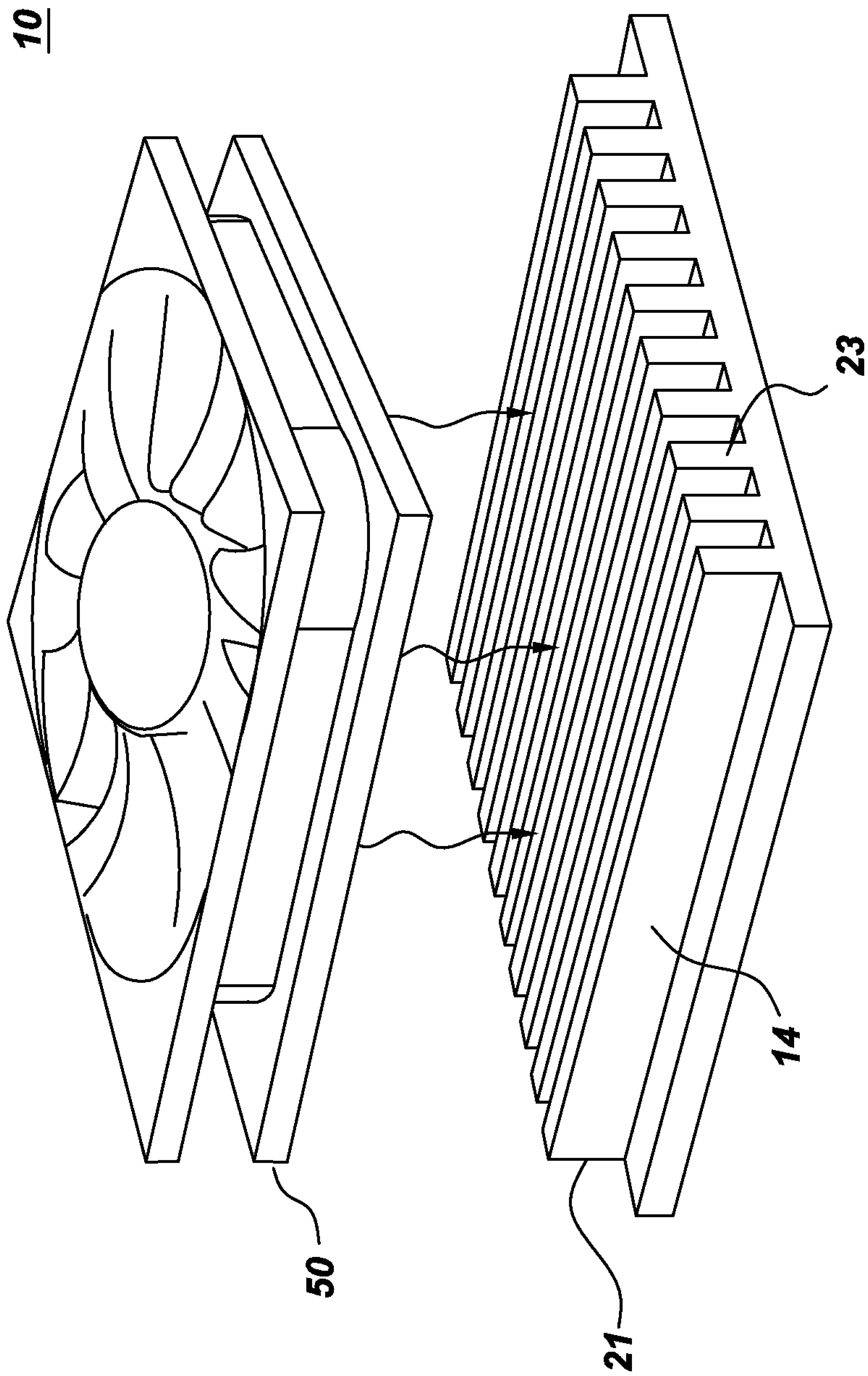

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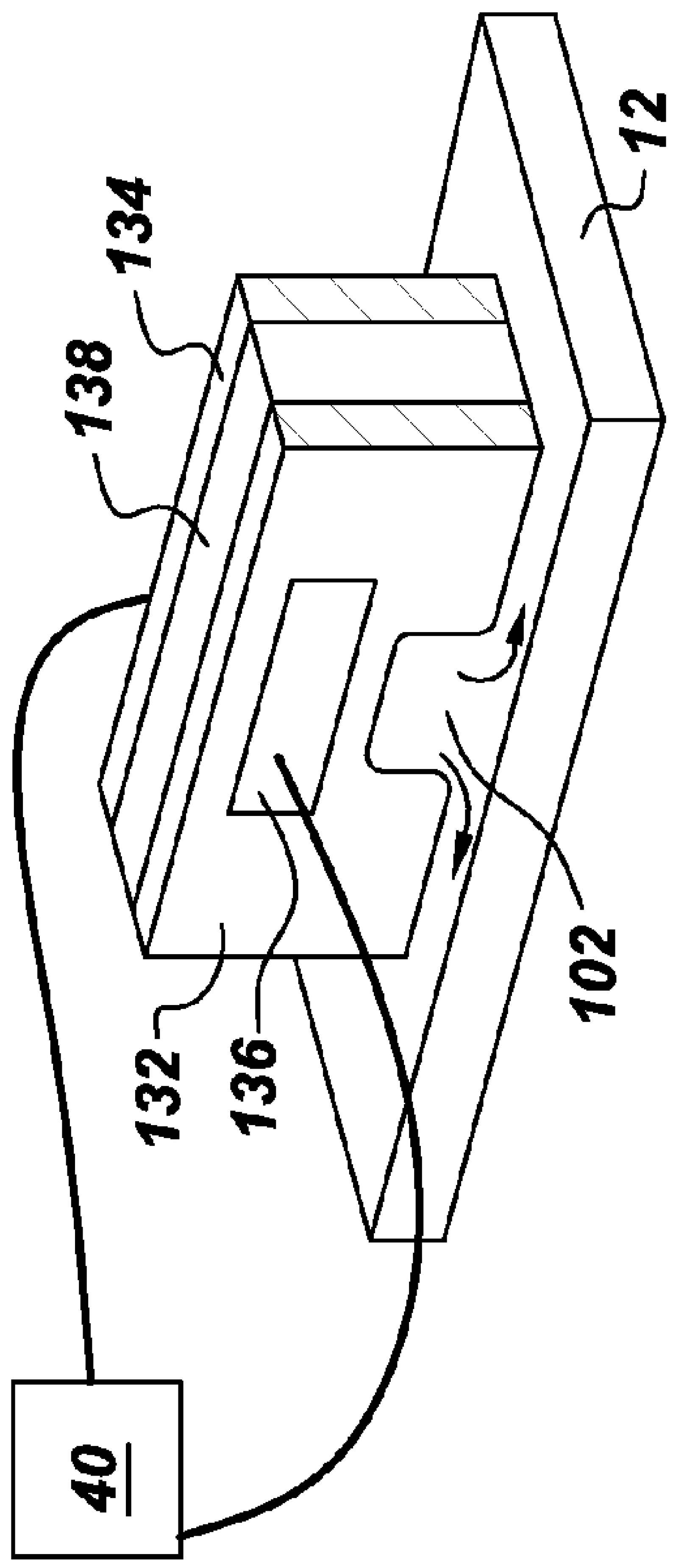

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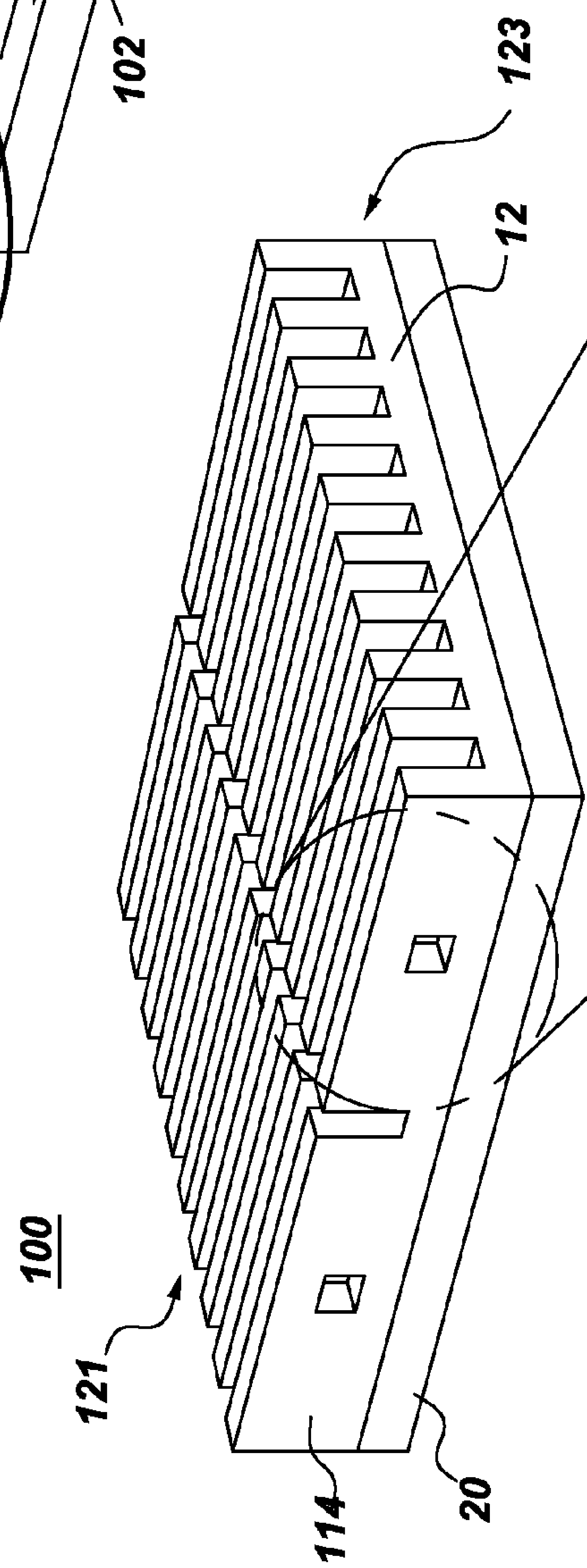

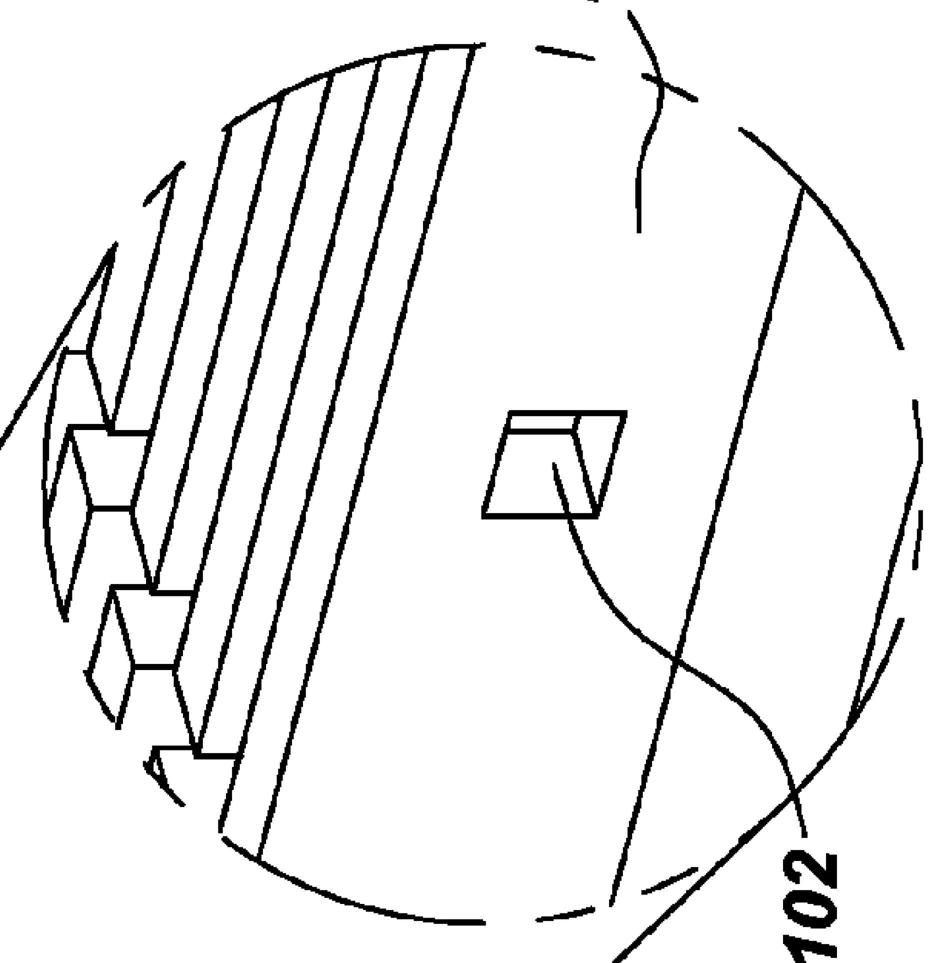

Fig. 10

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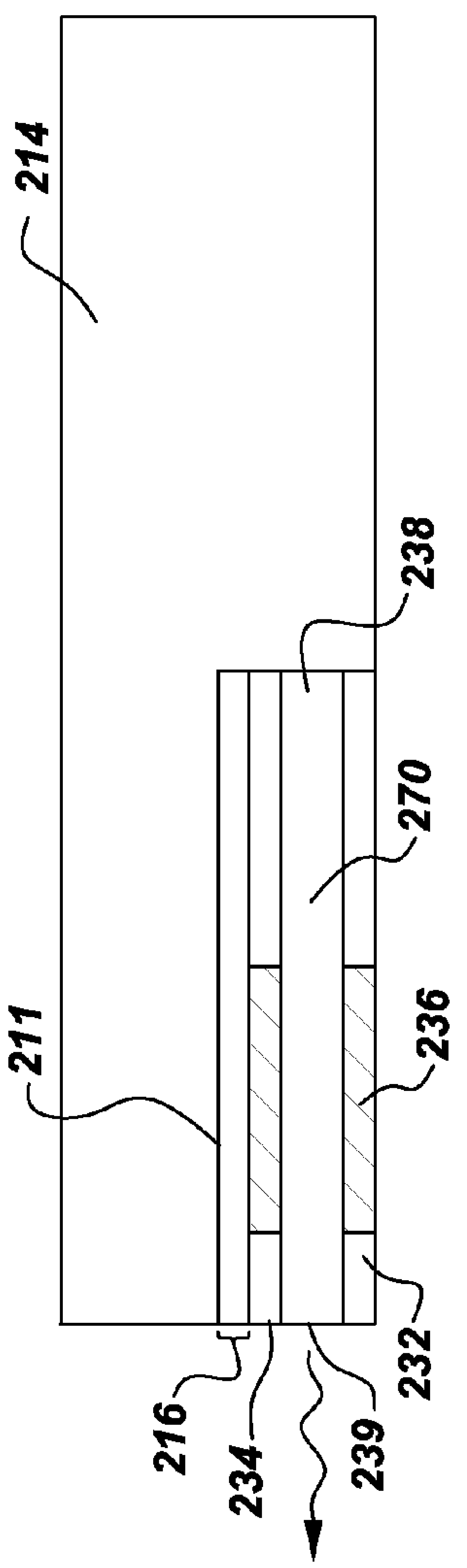

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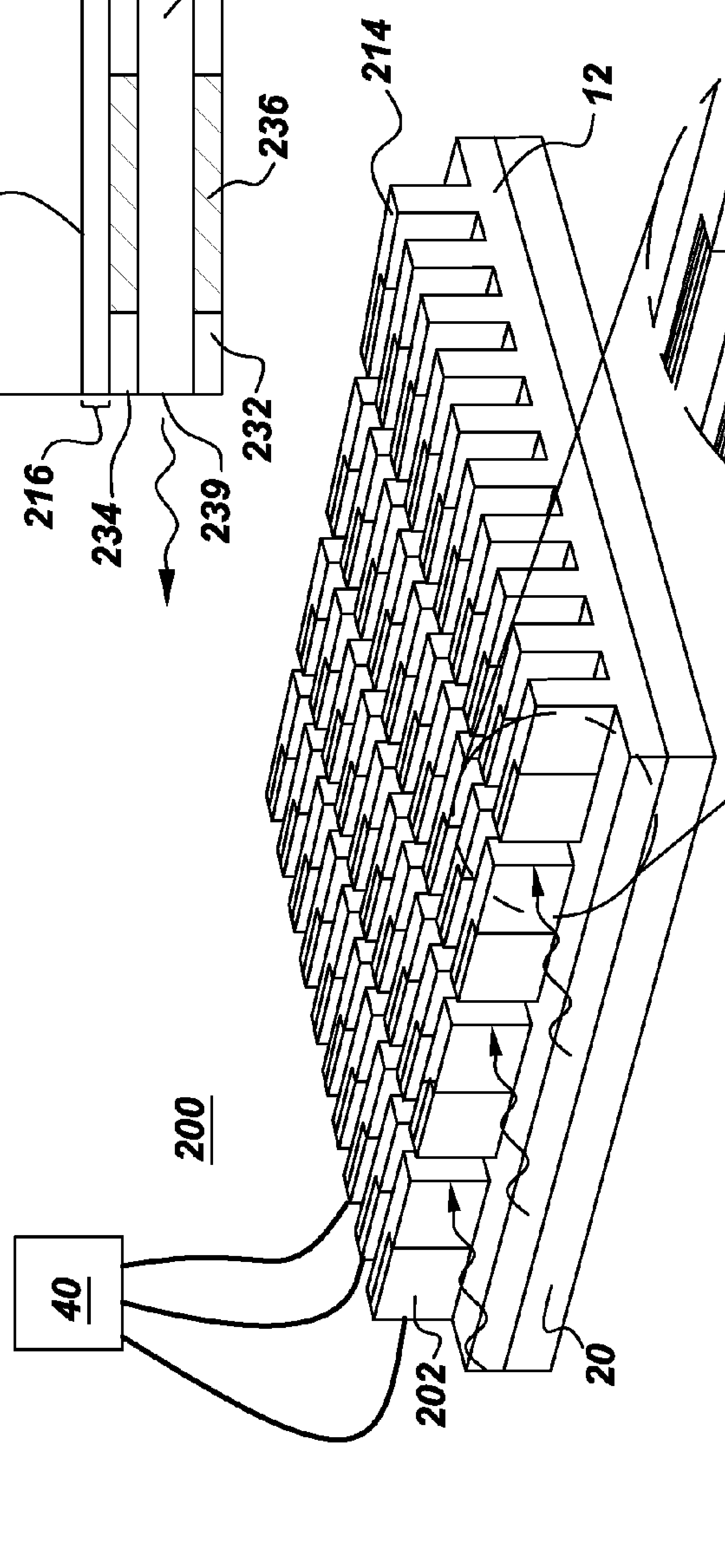

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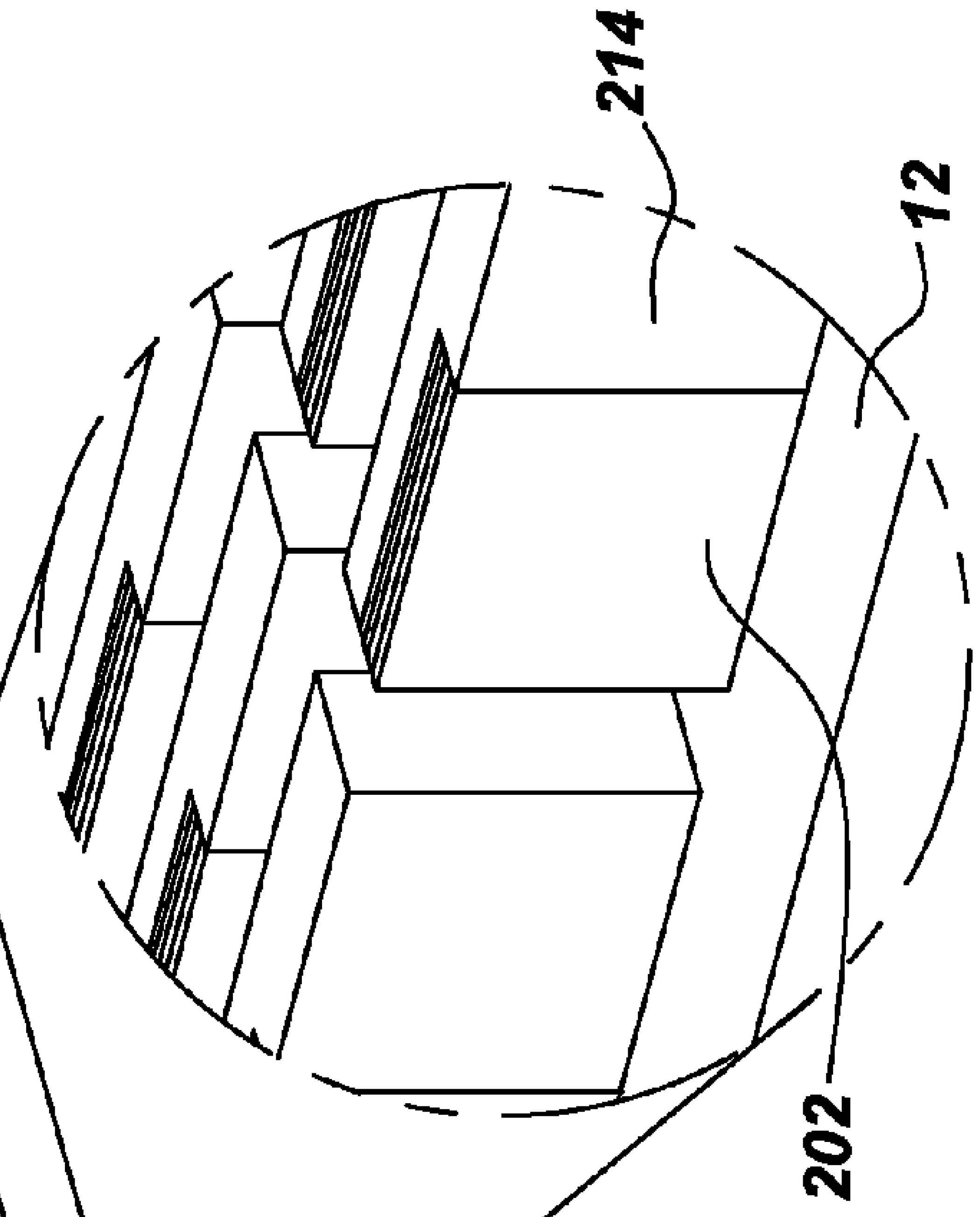

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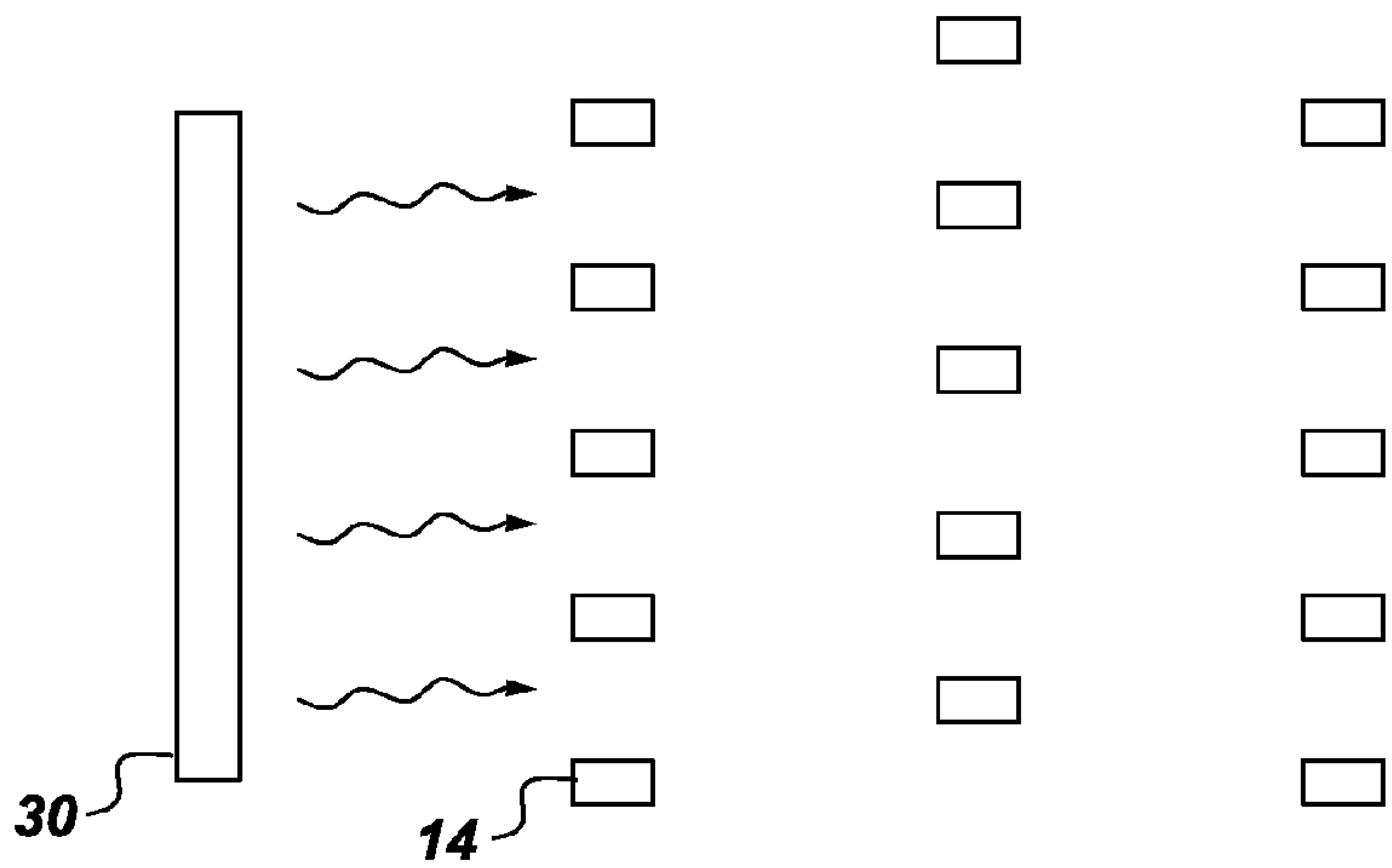

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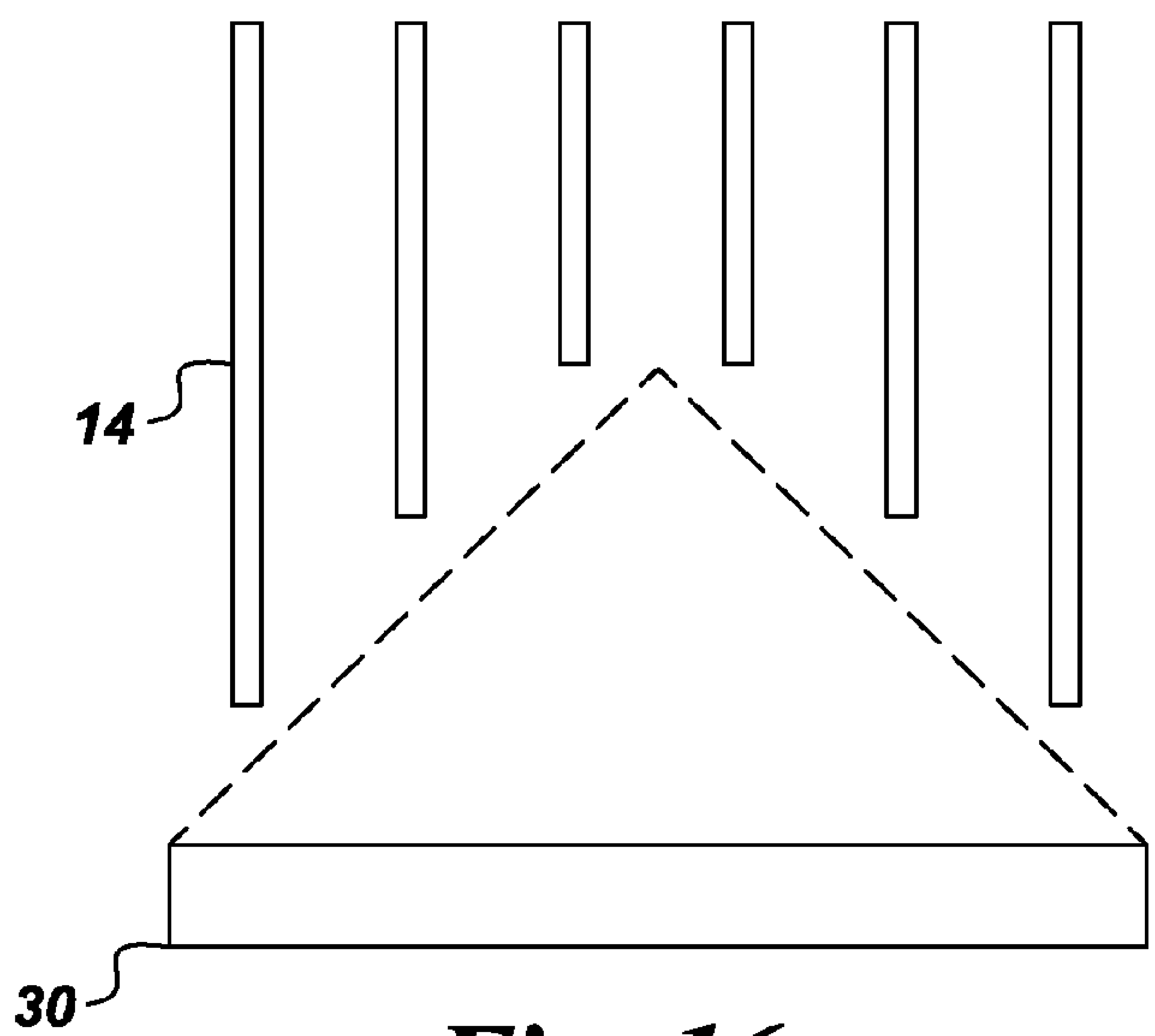

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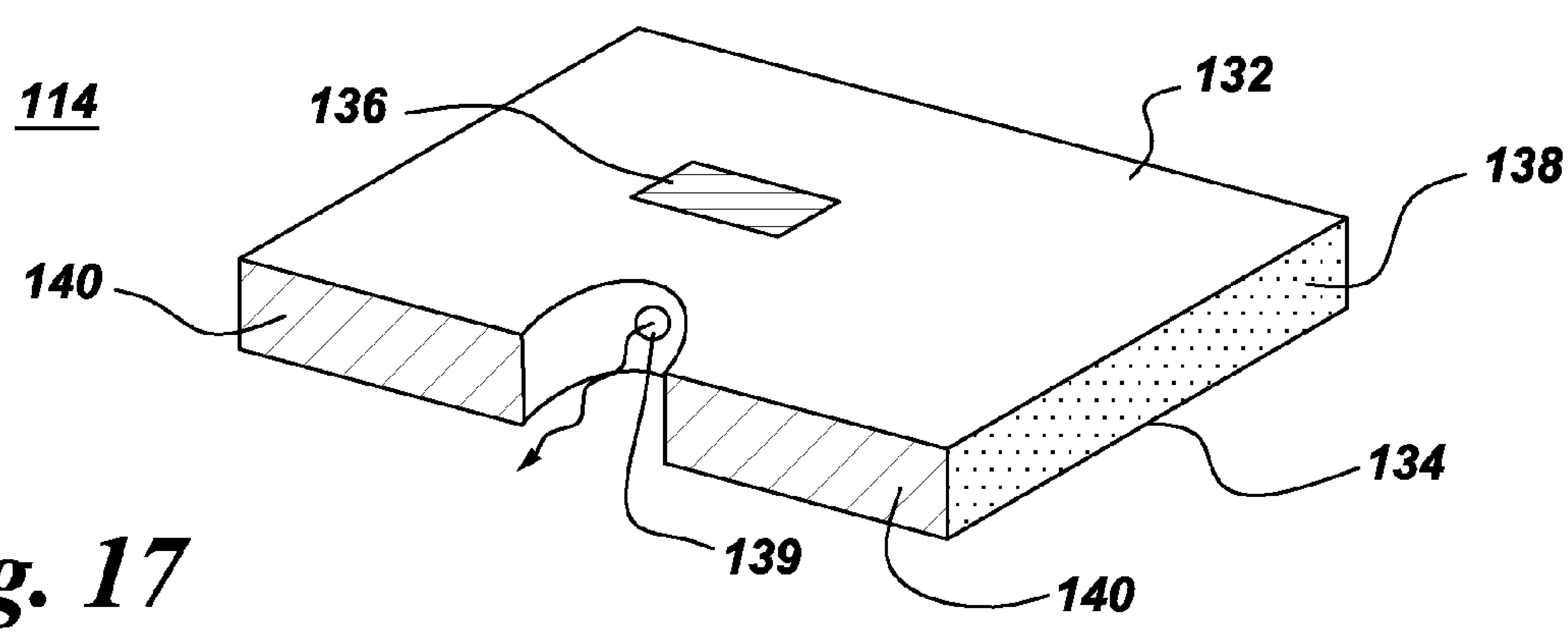

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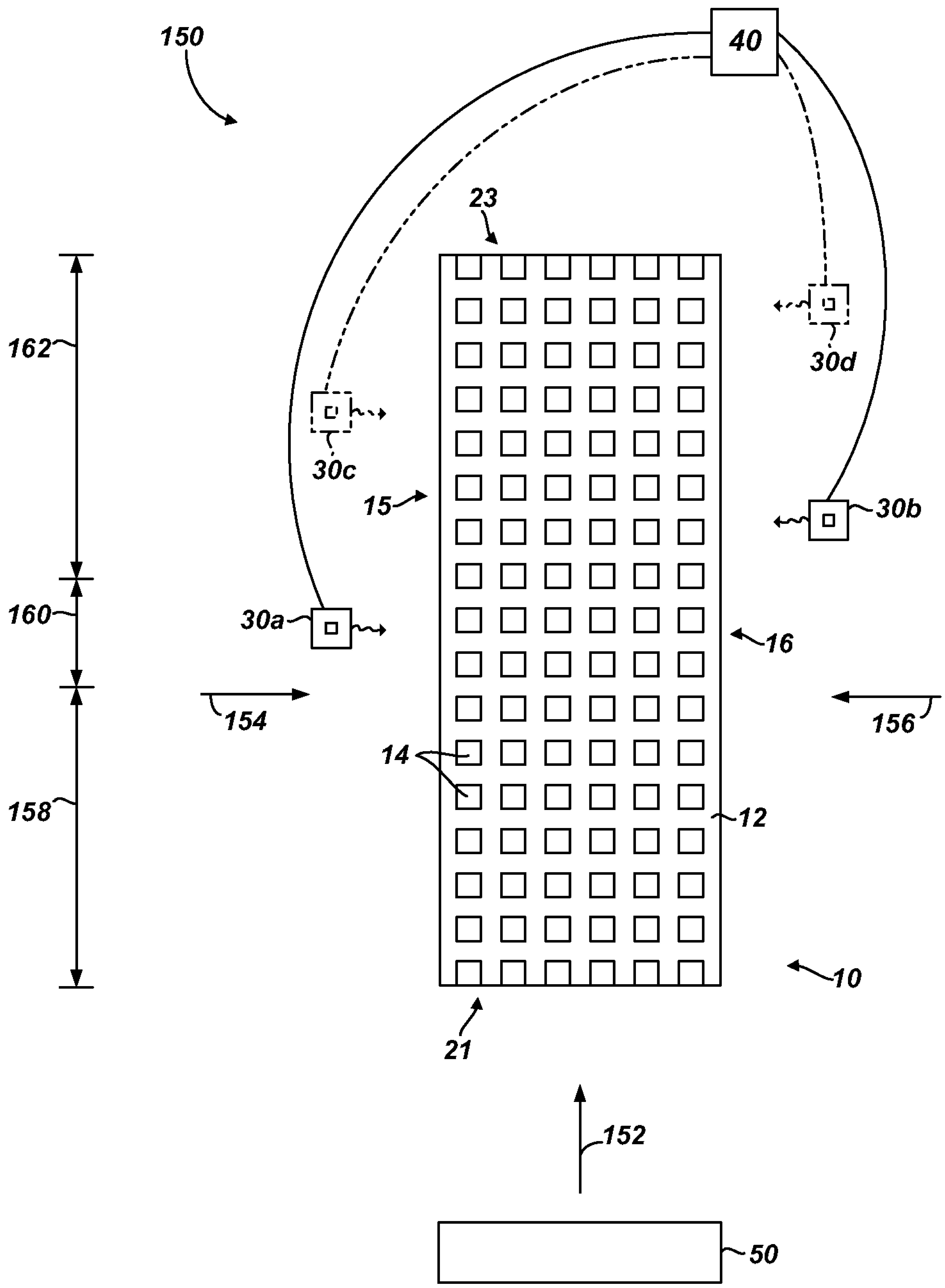
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Fig. 18

METHOD AND APPARATUS FOR IMPROVED COOLING OF A HEAT SINK USING A SYNTHETIC JET

CROSS-REFERENCE TO RELATED APPLICATION

The present application is a continuation-in-part of, and claims priority to, U.S. non-provisional application Ser. No. 12/421,068, filed Apr. 9, 2009, the disclosure of which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

The invention relates generally to thermal management systems, and more particularly to thermal management systems for use in embedded environments.

Environments having embedded electronic systems, hereinafter embedded environments or heated environments, offer challenges for thermal management. Such systems produce waste heat as a part of their normal operation, heat that must be removed for proper performance and reliability of the embedded electronics. The design of thermal management systems to provide cooling for embedded electronics is a formidable challenge due to space limitations. Examples of embedded electronic systems include single board computers, programmable logic controllers (PLCs), operator interface computers, laptop computers, cell phones, personal digital assistants (PDAs), personal pocket computers, and other small electronic devices, there is a limited amount of available space for thermal management systems. It has been known to use passive cooled heat sinks or forced air-cooling as thermal management systems to assist in the removal of heat from electronic components. Further, it has been known that conducting the heat generated by electronic components to a printed circuit board, on which they are mounted, provides a migration of the heat from a smaller area to a larger area. However, such techniques have limited heat removal capabilities.

Accordingly, there is a need for improved thermal management systems for embedded electronic systems.

BRIEF DESCRIPTION

In accordance with one aspect of the invention, a system for cooling a device includes a heat sink comprising a substrate having a plurality of fins arranged thereon, a fan positioned to direct an ambient fluid in a first direction across the heat sink, and a first synthetic jet assembly comprising one of a multi-orifice synthetic jet and a plurality of single orifice synthetic jets. The first synthetic jet assembly is configured to direct the ambient fluid in a second direction across the heat sink, wherein the second direction is approximately perpendicular to the first direction.

In accordance with another aspect of the invention, a method of fabricating a system for cooling an electronic device includes positioning a fan adjacently to a heat sink such that air flow from the fan is directed in a first direction through an array of fins of the heat sink. The method also includes positioning a first synthetic jet assembly adjacently to the heat sink such that air flow from the first synthetic jet assembly is directed in a second direction through the array of fins of the heat sink, wherein the second direction is approximately perpendicular to the first direction. The first synthetic jet assembly comprises one of a multi-orifice synthetic jet and a plurality of single orifice synthetic jets.

In accordance with another aspect of the invention, a cooling system includes a fan disposed adjacently to a heat sink to direct a first stream of ambient fluid through an array of fins of the heat sink and a first multi-orifice synthetic jet positioned adjacently to the heat sink to direct a second stream of ambient fluid through the array of fins of the heat sink. The first multi-orifice synthetic jet is positioned with respect to the fan such that the second stream of ambient fluid is approximately perpendicular to the first stream of ambient fluid.

Various other features and advantages will be made apparent from the following detailed description and the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawings illustrate preferred embodiments presently contemplated for carrying out the invention.

In the drawings:

FIG. **1** illustrates a heat sink with distributed jet cooling.

FIG. **2** is an enlarged view of a portion of the heat sink of FIG. **1** at a synthetic jet.

FIG. **3** depicts an example configuration for a multi-orifice synthetic jet for use in the heat sink of FIGS. **1** and **2**.

FIG. **4** depicts an example multi-stack synthetic jet assembly for use in the heat sink of FIGS. **1** and **2**.

FIG. **5** illustrates the expulsion of ambient air from a chamber in response to contraction of the flexible chamber walls.

FIG. **6** illustrates the ingestion of air into the chamber in response to expansion of the flexible chamber walls.

FIG. **7** illustrates a first fan location for a heat sink embodiment of the invention.

FIG. **8** illustrates a second fan location for a heat sink embodiment of the invention.

FIG. **9** illustrates another heat sink embodiment of the invention with distributed and integrated jet cooling.

FIG. **10** is an enlarged view of a portion of the heat sink of FIG. **9** at a synthetic jet.

FIG. **11** schematically depicts a single plate fin with an integrated synthetic jet for use in the heat sink of FIGS. **9** and **10**.

FIG. **12** illustrates another heat sink embodiment of the invention with distributed and integrated jet cooling.

FIG. **13** is an enlarged view of a portion of the heat sink of FIG. **12** showing several synthetic jets.

FIG. **14** schematically depicts, in cross-sectional view, an example configuration of a synthetic jet for use in the heat sink shown in FIGS. **12** and **13**.

FIG. **15** illustrates a v-groove configuration for the heat sink of FIGS. **1-6**.

FIG. **16** illustrates a v-groove plate fin configuration.

FIG. **17** illustrates a particular configuration of the fin of FIGS. **9-11** with enhanced thermal coupling to the base of the heat sink.

FIG. **18** schematically depicts a top view of an exemplary heat sink embodiment with forced convection and synthetic jet cooling.

DETAILED DESCRIPTION

FIGS. **1** and **2** illustrate a heat sink **10** with distributed jet cooling. As shown, for example, in FIG. **1**, the heat sink comprises a base **12** for thermal connection to at least one heated object **20**. The heated object **20** may be any object requiring cooling, non-limiting examples of which include high power processors and power electronics. The base **12** (base plate or sink plate) can be formed of a variety of thermally conductive materials, as known in the art. The heat sink **10** further includes an array of fins **14** thermally coupled to the base. The fins may be arranged in a two-dimensional array of "pin fins" as shown, for example in FIG. **1**. For other arrangements, the fins **14** may take the form of a one-dimensional array of "plate fins" defining slots between them, as shown for example in FIGS. **7** and **8**. Briefly, the heat from the heated object **20** is transferred into the base **12**, which in turn transfers heat into the fins **14**. The fins **14** increase the surface area for heat transfer for cooling the heated body **20**.

In the illustrated example, the heat sink **10** further includes at least one multi-orifice synthetic jet **30** disposed on a side **15**, **16** of the array of fins. In other example arrangements, multiple single jets are disposed on the respective side **15**, **16** of the array of fins. The multiple single jets are similar to the multi-orifice synthetic jets discussed herein, except that that the single jets include a single orifice. For the example illustrated in FIG. **3**, each of the multi-orifice synthetic jets **30** comprises a first flexible structure **32**, a second flexible structure **34**, at least one active material **36** coupled to at least one of the first and second flexible structures, and a compliant wall **38** positioned between the first and second flexible structures and defining a chamber. As indicated in FIG. **3**, the compliant wall defines multiple orifices **39** for facilitating fluid communication between the chamber and an ambient environment of the fins **14**. It should be noted that the number of orifices shown in FIG. **3** is merely illustrative and is non-limiting. In one non-limiting example, the compliant wall **38** comprises an elastomer. Other example materials for the compliant wall **38** include, without limitation, polymers, glues, adhesives, metals, and composites.

In the illustrated arrangement of FIG. **3**, the active material **36** is positioned on both of the first and second flexible structures **32**, **34**. It should be noted that the locations of the active materials **36** on the flexible structures **32**, **34** shown in the figures are purely illustrative, and the invention is not limited to any specific locations of active materials. In particular embodiments, the active material is coextensive with the respective flexible structure. In other embodiments, the active material extends over only a portion of the flexible structure. The active material can take the form of a single continuous portion. Alternatively, multiple discontinuous portions of the active material can be employed to actuate respective ones of the flexible structures. A suitable active material is one, which is capable of creating stress resulting from an electrical stimulus.

Examples of suitable active material include piezoelectric material, magnetostrictive material (magnetic fields from coils attract/oppose one another), shape-memory alloy, and motor imbalance (motor with a mass imbalance creates oscillatory motion). Within the subset of piezoelectric materials, suitable active materials include bimorph piezoelectric configurations, where two piezo layers are energized out of phase to produce bending; thunder configurations, where one piezo layer is disposed on a pre-stressed stainless steel shim; buzzer element configurations, where one piezo layer is disposed on a brass shim; and MFC configurations, where a piezo fiber composite on a flexible circuit is bonded to a shim. The active material may incorporate a ceramic material.

As indicated in FIG. **4**, the heat sink **10** may comprise a stack **60** of the single or multi-orifice synthetic jets **30**. Similar to the arrangement described with reference to FIGS. **1** and **2**, the stack **60** is disposed on one of the sides **15**, **16** of the array of fins **14**. Although FIG. **4** depicts a stack of two multi-orifice synthetic jets, the stack **60** may include any number of synthetic jets depending on the cooling application (for example, on the fin **14** height). The synthetic jets **30** may be separated by a spacer **42**, as indicated in FIG. **4**. In one non-limiting example, the spacer **42** comprises plastic.

As schematically depicted in FIG. **1**, a synthetic jet driver **40** is provided to apply an electrical current to the at least one active material **36**, to form streams of ambient air. The synthetic jet driver **40** can be electrically coupled to the active material **136** using wires or flexible interconnects, for example. Briefly, electrical current from synthetic jet driver **40** is received by the active material, and transformed into mechanical energy. As shown, for example in FIG. **5**, the active material **36** creates stress on the flexible walls **32**, **34**, causing them to flex inwardly, resulting in a chamber volume change and an influx of ambient air into the chamber **70**, and then outwardly, thereby ejecting the ambient air from the chambers **70** via the orifices **39**. Similarly, as illustrated in FIG. **6**, when the active material **36** creates stress on the flexible chamber walls **32**, **34** causing them to expand, resulting in another chamber volume change, ambient air is drawn into the chamber **70** via the orifices **39**. In this manner, the driver **40** actuates the jets **30**. The synthetic jet driver **40** may be co-located with the other heat sink elements or may be remotely located. The current may be provided as a sine wave, a square wave, a triangular wave, or any other suitable waveform, and it should be appreciated that the current is not to be limited to any specific waveform. However, it has been found that currents having lower harmonics, such as, for example, a sine wave, may be used to provide a quieter synthetic jet **30**. The voltage level for the electrical current may be between 1 and 150 volts but is not so limited. The frequency of the current may be between 2 and 300 hertz for embodiments requiring reduced noise, and between 300 hertz and 15 kilohertz for embodiments that do not require reduced noise levels.

For the example arrangement depicted in FIGS. **1** and **2**, the heat sink **10** comprises multiple multi-orifice synthetic jets **30** disposed on respective sides **15**, **16** of the array of fins **14**. In particular, for the arrangement of FIG. **1**, there are two multi-orifice synthetic jets **30** disposed on the respective sides **15**, **16** of the array of fins **14**. As indicated by the arrows in FIG. **2**, for this example arrangement, the orifices may be disposed, so as to direct air between the fins **14** and to draw air from between the fins **14**.

The orifices **39** may be configured in a variety of arrangements depending on the desired cooling flow and on the configuration of the array of fins **14**. In one example arrangement, at least a subset of the orifices **39** are positioned to eject an ambient fluid directly on the fins **14**. In another example arrangement, at least a subset of the orifices **39** are oriented at an angle transverse to an opposing surface **11** of the fins **14**. For certain configurations, the ambient fluid is ejected perpendicular to a plane of the fins **14**, as indicated for example in FIG. **5**.

As shown, for example, in FIG. **7**, for particular embodiments, the heat sink **10** further comprises a fan **50** disposed on one of an inlet and an outlet side **21**, **23** of the array of fins **14**. The fan **50** is configured to draw the ambient fluid through the fins **14**, and the ambient fluid drawn by the fan **50** interacts with the ambient fluid ejected from the multi-orifice synthetic jets or from the multiple single jets to further enhance the cooling by at least ten percent (10%) relative to a jet-free condition. For configurations having the fan **50** disposed at the inlet side **21** of the fins **14**, the fan **50** is configured to push flow towards the array of fins. Similarly, fans **50** disposed at the outlet side **23** of the array of fins are configured to pull flow through the array. FIG. **8** illustrates another arrangement, in which the fan **50** is disposed above the array of fins **14** and configured to blow an ambient fluid on the fins **14**.

A number of different fin configurations can be employed for the heat sink of FIGS. **1-6**. For the arrangement depicted in FIG. **1**, the fins **14** are pin fins and are arranged in a regular array. FIG. **15** illustrates another pin fin configuration for the heat sink **10** of FIGS. **1-6**, in which the fins **14** are staggered (offset) to provide a v-groove cooling configuration. FIG. **16** illustrates a v-groove plate fin configuration. Under specific circumstances, computer simulation results have demonstrated a thirty percent performance enhancement for the v-groove configuration relative to the conventional plate fin arrangement shown for example in FIGS. **7** and **8**. This enhanced cooling is due in large part to more efficient confinement of the vortices in the v-groove heat sink fin arrays. Unlike the air flow from a fan, the flow field surrounding the vortex dipoles consists of velocity vectors which are not largely parallel to the heat sink fin gaps. As a result, as these vortices approach a conventional heat sink (without grooving), their local approach velocities may not be well-aligned with the fin gaps, causing an imperfect transfer of momentum to the air in the gaps. The v-grooving improves the entrapment of this momentum contained within the dipoles and enhances the heat transfer off the heat sink. It should be noted that although FIGS. **15** and **16** show v-groove configurations with symmetric v-grooves, the invention is not limited to these arrangements and can also employ asymmetric v-groove configurations. Similarly, although FIGS. **15** and **16** show v-grooves with centerlines aligned with the respective centerlines of the jets, offset arrangements may also be employed, in which the centerlines of the v-grooves are offset from the centerlines of the jets. Similarly, combinations of these arrangements may also be employed (asymmetric v-grooves that are offset for the respective jets).

FIGS. **9-11** illustrate another heat sink **100** embodiment of the invention with distributed and integrated jet cooling. As shown for example in FIG. **9**, the heat sink **100** includes a base **12** for thermal connection to at least one heated object **20**. As discussed above, the invention is not limited to cooling a specific type of heated object, but rather can be used to cool a variety of heated objects. The heat sink **100** further includes an array of fins **114** thermally coupled to the base **12**. For the example configuration shown in FIG. **9**, a two-dimensional array of "plate fins" is employed. Respective ones of at least a subset of the fins comprise a synthetic jet **102** configured to eject an ambient fluid into an ambient environment of the fins and base. In specific embodiments, a synthetic jet **102** is inset into each of the fins **114**. The synthetic jets **102** are shown in greater detail in FIG. **10**.

FIG. **11** schematically depicts a single plate fin **114** with an integrated synthetic jet for use in the heat sink of FIGS. **9** and **10**. As shown in FIG. **11**, each of the fins **114** with an integrated jet **102** comprises a first flexible structure **132**, a second structure **134**, and at least one active material **136** coupled to the first flexible structure **132**. The active material **136** is discussed above with reference to heat sink **10**. For the integrated embodiment of FIGS. **9-11**, example materials for the flexible structures **132**, **134** include, without limitation, metal-based materials, such as aluminum and copper, composite structures, for example, carbon fiber filled materials, and thermally conductive polymer based materials. A compliant wall **138** is positioned between the first and second structures **132**, **134** thereby forming a chamber. The compliant wall **138** defines at least one orifice **139** for facilitating fluid communication between the chamber and the ambient environment.

According to a more particular embodiment, the second structure **134** is flexible, and the active material **136** is coupled to at least one of the first and second flexible structures **132**, **134**. In more particular embodiments, active material **136** is coupled to both flexible structures **132**, **134**, such that both of these walls are actuated. As discussed above, the active material can take the form of a single continuous portion. Alternatively, multiple discontinuous portions of the active material can be employed to actuate respective ones of the flexible structures.

FIG. **17** illustrates a particular configuration of the fin **114** of FIGS. **9-11** with enhanced thermal coupling to the base of the heat sink. For the example configuration shown in FIG. **17**, each of the fins **114** with an integral jet further comprises at least one thermally conductive portion **140** extending between the first and second structures **132**, **134** and disposed to thermally couple the fin to the base **12**. In the illustrated example shown in FIG. **17**, the fin **114** includes two thermally conductive portions **140**. Non-limiting example materials for the thermally conductive portions **140** include metals, such as copper. In example arrangements the thermally conductive portions **140** are attached to the base plate, for example by brazing.

For the example shown in FIG. **11**, at least one synthetic jet driver **40** is provided to actuate one or more of the synthetic jets **102**. The synthetic jet driver **40** can be electrically coupled to the active material **136** using wires or flexible interconnects, for example. As noted above, the synthetic jet driver **40** may be co-located with the other heat sink elements or may be remotely located. The operation of the synthetic jets **102** is similar to that of multi-orifice synthetic jets **30** described above with reference to FIGS. **5** and **6**.

Advantages of the heat sink **100** embodiment described with reference to FIGS. **9-11** and **17** include a compact, relatively light design with increased surface area. In addition, the design is rugged, in that the active material is inherently protected by the fins.

Further, the synthetic jets **102** can be used alone or in combination with one or more fans **50**, depending on the application. As discussed above with reference to FIG. **7**, a fan **50** may be disposed on one of an inlet and an outlet side **121**, **123** of the array of fins **114**. The fan is configured to draw the ambient fluid through the fins **114**, such that the ambient fluid drawn by the fan **50** interacts with the ambient air ejected from the synthetic jets **102** to further enhance the cooling. Similarly, as discussed above with reference to FIG. **8**, a fan **50** may be disposed above the array of fins **114** and configured to blow the ambient fluid on the fins **114**.

FIGS. **12-14** illustrate another heat sink **200** embodiment of the invention with distributed and integrated jet cooling. As shown for example in FIG. **12**, the heat sink **200** includes a base **12** for thermal connection to at least one heated object **20**. As discussed above, the heated object **20** may be any object requiring cooling. The heat sink **200** further includes an array of fins **214** thermally coupled to the base **12**. At least a subset of the fins comprise synthetic jets **202** configured to eject an ambient fluid into an ambient environment of the fins **214** and base **12**. For the example configuration shown in FIGS. **12** and **13**, each of the fins **214** is coupled to a synthetic jet **202**. However, for other arrangements (not shown) synthetic jets **202** are provided for only a subset of the fins **214**.

FIG. **14** schematically depicts, in cross-sectional view, an example configuration of a synthetic jet **202** for use in the heat sink shown in FIGS. **12** and **13**. For the example configuration shown in FIG. **14**, the synthetic jet **202** comprises at least one flexible structure **232**, a second structure **234**, and at least one active material **236** coupled to the flexible structure **232**. A compliant wall **238** is positioned between the flexible structure **232** and the second structure **234**, thereby defining a chamber. The compliant wall defines at least one orifice, which is indicated by reference numeral **239**, for facilitating fluid communication between the chamber and the ambient environment. Example active materials and example materials for the compliant wall are discussed above. Example materials for flexible structures **232**, **234** include, but are not limited to metals, conductive polymers, and plastics.

For the example arrangement shown in FIG. **14**, the second structure **234** comprises a second flexible structure **234**, and the active material **236** is coupled to at least one of the first and second flexible structures. For the particular configuration shown in FIG. **14**, the active material **236** is coupled to both flexible structures **232**, **234**, such that both structures can be actuated, for example upon application of an electric current. Further, for the arrangement shown in FIG. **14**, the second flexible structure **234** is separated from the surface **211** of the fin **214** by a gap **216** when the synthetic jet **202** is in an unactuated state.

The operation of synthetic jet **202** is similar to that of synthetic jet **30**, as discussed above with reference to FIGS. **5** and **6**. Typically, a synthetic jet driver **40** is provided to apply an electrical current to the at least one active material **236**, to form streams of ambient air. The synthetic jet driver **40** can be electrically coupled to the active material **236** using wires or flexible interconnects, for example. Briefly, upon application of an electrical current from synthetic jet driver **40**, the active material **236** creates stress on the flexible wall **232** causing it to flex inwardly, resulting in a chamber volume change and an influx of ambient air into the chamber **270**, and then outwardly, thereby ejecting the ambient air from the chamber **270** via the orifice **239**. Similarly, when the active material **236** creates stress on the flexible chamber walls **232** it to expand, resulting in another chamber volume change, ambient air is drawn into the chamber **270** via the orifice **239**. In this manner, the driver **40** actuates the jet **202**. As note above, the synthetic jet driver **40** may be co-located with the other heat sink elements or may be remotely located. The current may be provided as a sine wave, a square wave, a triangular wave, or any other suitable waveform, and it should be appreciated that the current is not to be limited to any specific waveform.

Further, the synthetic jets **202** can be used alone or in combination with one or more fans **50**, depending on the application. As discussed above with reference to FIG. **7**, a fan **50** may be provided on one of an inlet and an outlet side **221**, **223** of the array of fins **214**, where the fan is configured to draw the ambient fluid through the fins, and where the ambient fluid drawn by the fan interacts with the ambient air ejected from the synthetic jets to further enhance the cooling. Similarly, and as discussed above with reference to FIG. **8**, a fan **50** may be provided above the array of fins **214** and configured to blow the ambient fluid on the fins.

FIG. **18** illustrates a cooling system **150** that includes heat sink **10** and fan **50**, according to another embodiment of the invention. As shown, fan **50** is positioned at inlet side **21** of heat sink **10** to direct ambient fluid across base **12** and array of fins **14** toward outlet side **23**. One skilled in the art will readily recognize that fan **50** may alternatively be positioned at outlet side **23** of heat sink **10**, so as to draw the ambient fluid through and away from base **12** and array of fins **14** of heat sink **10**. Fins **14** may be arranged in a rectangular array, such as shown in FIGS. **1**, **12**, and **18** or as a staggered array, such as shown in FIG. **15** as an example.

Cooling system **150** also includes at least two synthetic jets **30***a*, **30***b* positioned on respective sides **15**, **16** of heat sink **10**. Optionally, cooling system **150** includes additional synthetic jets, such as optional jets **30***c*, **30***d* (shown in phantom), positioned adjacently to heat sink **10**. According to alternative embodiments, synthetic jets **30***a*, **30***b* and optional jets **30***c*, **30***d* may be configured as multi-orifice synthetic jets, similar to jets **30** illustrated in FIG. **3**, or as individual synthetic jets that include a single orifice. While cooling system **150** is shown as including four synthetic jets **30***a-d*, one skilled in the art will recognize that the number of jets may be selected based on the system specifications and desired cooling characteristics.

In operation, fan **50** and synthetic jets **30***a-d* operate together to cool heat sink **10**. Fan **50** directs a stream of ambient fluid across base **12** and array of fins **14** of heat sink **10** in direction **152** such that the ambient fluid ejected from fan **50** flows from inlet side **21** of heat sink **10** toward outlet side **23**. Synthetic jets **30***a-d* enhance heat transfer by directing cool ambient fluid that has bypassed the heat sink **10** back towards it. As shown in FIG. **18**, synthetic jets **30***a*, **30***c* are positioned to eject streams of fluid in direction **154** across the width of heat sink **10** through array of fins **14**. Synthetic jets **30***b*, **30***d* are positioned to eject streams of fluid in direction **156**, which is opposite direction **154**. Thus, jets **30***a*, **30***c* and jets **30***b*, **30***d* eject fluid across heat sink **10** in directions approximately perpendicular to the direction of fluid flow from fan **50**. In one exemplary embodiment, fan **50** is sized to direct a stream of ambient fluid at a velocity not more than half the velocity of the stream of ambient fluid that is ejected from jets **30***a-d*.

As the ambient fluid from fan **50** passes across heat sink **10**, the temperature of the ambient fluid increases as it travels from upstream section **158**, across central section **160**, and then across downstream section **162**. Thus, the effectiveness of the convective cooling from fan **50** decreases in direction **152** along the length of heat sink **10**. Synthetic jets **30***a-d* enhance cooling of heat sink **10** by directing ambient fluid toward heat sink **10** that is cooler than the fluid from fan **50**, which was been heated as it passes along the length of heat sink **10**. Accordingly, in one embodiment, a first synthetic jet **30***a* is positioned approximately halfway along length of heat sink **10**, aligned with a central section **160** of heat sink **10**, to direct cooler fluid from the vicinity of the heat sink **10** into the array of fins **14**. The cooler fluid from synthetic jet **30***a* mixes with the heated fluid from fan **50** and enhances convective cooling across heat sink **10**. As shown in FIG. **18**, synthetic jet **30***b* and optional jets **30***c*, **30***d*, are positioned farther downstream than jet **30***a*, adjacent to a downstream section **162** of heat sink **10**, to provide additional cooling enhancement as the fluid from fan **50** that flows in direction **152** across heat sink **10** increases in temperature. One skilled in the art will recognize that the position of jets **30***a-d* along heat sink **10** may be selected based on design specifications and desired cooling characteristics.

As further shown in FIG. **18**, synthetic jets **30***a*, **30***b* and optional jets **30***c*, **30***d* may be positioned in a staggered pattern along the length of heat sink **10** such that they are not directly aligned with one another. As such, the flow of air ejected from a jet positioned on side **15** of heat sink **10**, such as synthetic jet **30***a* or **30***c*, does not directly oppose the flow from a jet positioned on side **16** of heat sink **10**, such as synthetic jet **30***b* or **30***d*. In one embodiment, synthetic jets **30***a-d* are staggered adjacently to a sub-portion of the length of the heat sink **10** that includes central section **160** and downstream section **162**. Alternatively, jets **30***a*, **30***b* may be positioned on a common side of heat sink, such as side **15**, for example.

Therefore, in accordance with one embodiment, a system for cooling a device includes a heat sink comprising a substrate having a plurality of fins arranged thereon, a fan positioned to direct an ambient fluid in a first direction across the heat sink, and a first synthetic jet assembly comprising one of a multi-orifice synthetic jet and a plurality of single orifice synthetic jets. The first synthetic jet assembly is configured to direct the ambient fluid in a second direction across the heat sink, wherein the second direction is approximately perpendicular to the first direction.

In accordance with another embodiment, a method of fabricating a system for cooling an electronic device includes positioning a fan adjacently to a heat sink such that air flow from the fan is directed in a first direction through an array of fins of the heat sink. The method also includes positioning a first synthetic jet assembly adjacently to the heat sink such that air flow from the first synthetic jet assembly is directed in a second direction through the array of fins of the heat sink, wherein the second direction is approximately perpendicular to the first direction. The first synthetic jet assembly comprises one of a multi-orifice synthetic jet and a plurality of single orifice synthetic jets.

In accordance with yet another embodiment, a cooling system includes a fan disposed adjacently to a heat sink to direct a first stream of ambient fluid through an array of fins of the heat sink and a first multi-orifice synthetic jet positioned adjacently to the heat sink to direct a second stream of ambient fluid through the array of fins of the heat sink. The first multi-orifice synthetic jet is positioned with respect to the fan such that the second stream of ambient fluid is approximately perpendicular to the first stream of ambient fluid.

This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

What is claimed is:

1. A system for cooling a device comprising:

a heat sink comprising a substrate having a plurality of fins arranged thereon;

a fan positioned to direct a stream of ambient fluid in a first direction towards the heat sink; and

a first synthetic jet assembly comprising one of a multi-orifice synthetic jet and a plurality of single orifice synthetic jets;

wherein the first synthetic jet assembly is configured to direct ambient fluid in a second direction across the heat sink, wherein the second direction is approximately perpendicular to the first direction;

wherein a first portion of the stream of ambient fluid directed by the fan flows across the heat sink and a second portion of the stream of ambient fluid directed by the fan bypasses the heat sink; and

wherein the second portion of the stream of ambient fluid that bypasses the heat sink is directed back toward the heat sink by the first synthetic jet assembly.

2. The system of claim **1** wherein the fan is positioned at a first side of the heat sink, the fan configured to direct the ambient fluid across a length of the heat sink; and

wherein the first synthetic jet assembly is positioned at a second side of the heat sink adjacent to the first side, the first synthetic jet assembly configured to direct the ambient fluid across a width of the heat sink.

3. The system of claim **1** wherein the plurality of fins comprises an array of pin fins.

4. The system of claim **3** wherein the plurality of fins comprises a rectangular array of pin fins.

5. The system of claim **3** wherein the plurality of fins comprises a staggered array of pin fins.

6. The system of claim **1** wherein the heat sink comprises an upstream section, a downstream section, and a central section between the upstream section and the downstream section; and

wherein the first synthetic jet assembly is aligned with at least one of the central section and the downstream section of the heat sink.

7. The system of claim **1** further comprising a second synthetic jet assembly positioned adjacent to a third side of the heat sink, the third side opposite the second side of the heat sink.

8. The system of claim **7** wherein the synthetic jets of the first synthetic jet assembly are positioned in a staggered pattern along a sub-portion of the length of the heat sink with respect to the synthetic jets of the second synthetic jet assembly.

9. The system of claim **1** wherein the fan is sized to direct ambient fluid at a velocity not more than half the velocity of ambient fluid provided from the first synthetic jet assembly.

10. A method of fabricating a system for cooling an electronic device comprising:

providing and positioning a fan adjacently to a heat sink such that air flow from the fan is directed in a first direction through an array of fins of the heat sink; and

providing and positioning a first synthetic jet assembly adjacently to the heat sink such that air flow from the first synthetic jet assembly is directed in a second direction through the array of fins of the heat sink, wherein the second direction is approximately perpendicular to the first direction, and wherein the first synthetic jet assembly comprises one of a multi-orifice synthetic jet and a plurality of single orifice synthetic jets;

wherein, in providing the fan, a fan is provided that is sized to direct a stream of ambient fluid at a velocity not more than half the velocity of the air flow provided from the one of the multi-orifice synthetic jet and the plurality of single orifice synthetic jets.

11. The method of claim **10** further comprising positioning the fan adjacently to an inlet side of the heat sink such that air flow from the fan is directed along a length of the heat sink toward an outlet side thereof.

12. The method of claim **10** further comprising:

positioning the first synthetic jet assembly adjacently to a first side of the heat sink such that air flow from the first synthetic jet assembly is directed along a width of the heat sink; and positioning a second synthetic jet assembly adjacently to a second side of the heat sink such that air flow from the second synthetic jet assembly is directed along the width of the heat sink in a direction opposite a direction of air flow from the first synthetic jet assembly.

13. The method of claim **12** further comprising positioning the second synthetic jet assembly adjacently to the second side of the heat sink such that air flow from the second synthetic jet assembly is non-opposing to air flow from the first synthetic jet assembly.

14. The method of claim **10** wherein a first portion of the air flow directed by the fan flows across the heat sink and a second portion of the air flow directed by the fan bypasses the heat sink; and

wherein the second portion of the air flow that bypasses the heat sink is directed back toward the heat sink by the first synthetic jet assembly.

15. A cooling system comprising:

a fan disposed adjacently to a heat sink to direct a first stream of ambient fluid through an array of fins of the heat sink;

a first multi-orifice synthetic jet positioned adjacently to the heat sink to direct a second stream of ambient fluid through the array of fins of the heat sink; and

a synthetic jet driver electrically coupled to the first multi-orifice synthetic jet to actuate the first multi-orifice synthetic jet;

wherein the first multi-orifice synthetic jet is positioned with respect to the fan such that the second stream of ambient fluid is approximately perpendicular to the first stream of ambient fluid; and

wherein the fan is sized to direct the first stream of ambient fluid at a velocity not more than half the velocity of the second stream of fluid provided from the first multi-orifice synthetic jet.

16. The cooling system of claim **15** wherein the fan is disposed at an inlet side of the heat sink; and

wherein the first multi-orifice synthetic jet is disposed at a first side of the heat sink, the first side adjacent to the inlet side.

17. The cooling system of claim **15** further comprising a second multi-orifice synthetic jet positioned adjacently to the heat sink to direct a third stream of ambient fluid through the array of fins of the heat sink.

18. The cooling system of claim **17** wherein the second multi-orifice synthetic jet is positioned at a second side of the heat sink, the second side opposite the first side.

19. The cooling system of claim **17** wherein the first multi-orifice synthetic jet is positioned a first distance from an intersection of the first side with the inlet side of the heat sink; and

wherein the second multi-orifice synthetic jet is positioned a second distance from an intersection of the second side with the inlet side of the heat sink, the second distance greater than the first distance.

20. The cooling system of claim **15** wherein the fan is sized to direct the first stream of ambient fluid at a first velocity; and

wherein the first multi-orifice synthetic jet is sized to direct the second stream of ambient fluid at a second velocity, the second velocity greater than the first velocity.

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